What is Scanning Probe Microscopy?

Scanning Probe Microscopy (SPM) is a catch-all phrase for numerous techniques that probe matter at 100-μm to sub-nm length scales by sensing “near-field” interactions with a sharp physical probe. Unlike electron microscopy, which requires vacuum and (usually) special sample preparation, SPMs typically work in air with minimal sample preparation (but also in liquid, e.g., for biological applications, requiring more in the way of sample preparation). Unlike electron and light microscopy, the principal image does not involve lensing or the scattering intensity of electrons, photons or any other fundamental particle. Under the SPM umbrella we find Atomic Force Microscopy (AFM) and related imaging techniques. Each SPM raster scans the surface of the sample (point-by-point, line-by-line) to create a map of the surface. The probes, techniques, and maps are diverse. The simplest, “0th-order” map is of the (3-dimensional) topography. Importantly this is a digital map of topography, so height and roughness information is obtained directly and quantitatively from the image (not from line-of-sight). Other (“higher order”) maps distinguish regions that differ from one another in behavior, contrasting mechanical, dielectric, capacitive, magnetic, thermal, and other properties of materials.

Which techniques will I learn?

In basic training we cover the three fundamental surface tracking modes: (i) contact mode (continuous sliding), (ii) fast force(-distance) curve mapping (trade names peak force QNM or pulsed force mode), and (iii) dynamic mode (the amplitude modulation variant, trade names AC or “tapping”, though the latter term can be misleading), operated in ambient air. Contact mode and peak/pulsed force modes are treated as quasistatic techniques, meaning that each contact is in a vertical force balance as described by adhesive contact mechanics. (Models predict that contact radius increases with contact force and probe radius of curvature as well as surface energy (polarizability), and decreases with sample modulus. I.e., these variables determine resolution.) In contact mode friction is present, indicating dissipative (irreversible) processes during sliding. These friction forces are sensitive to atomic and molecular structure (thus material properties) and can be imaged simultaneously to topography. Among other things, friction is sensitive to chemistry and thereby surface contamination (i.e., frictional imaging can serve as a diagnostic). Force curves involve the approach and retraction of tip to sample once per measurement location, and thereby are sensitive to the (1) vertical stiffness of individual tip-sample contacts, and thereby the mechanical properties of the sample; and (2) the stickiness of each contact as the tip is pulled off the surface, and thereby surface chemistry. (1 and 2 again can serve as diagnostics.) In dynamic mode the probe is instead oscillated normal to the sample at the high resonance frequency of the cantilever to which the tip is attached, such that here too the tip and sample intermittently interact; but the measurement averages over hundreds of interactive cycles per site. These interactions may or may not involve solid contact. In addition, a time lag (phase lag) between the driving oscillation and the actual probe-sample interaction is sensitive to energy dissipation per encounter, and thereby material properties. This phase lag can be imaged simultaneous to topography.

Which mode should I use in my research?

It is best to be open to using all three modes and their complementary advantages. Contact mode is usually fastest, and friction provides the strongest materials contrast on many inorganics. Contact mode doesn’t work well if the probe-sample interaction is too strong, resulting in damaging shear forces. This is often the case on materials that are soft or weakly attached to a substrate. (On the other hand abrasion can be exploited for film thickness measurements, to interrogate film-substrate adhesion, or to probe material cohesion.) In contact mode there can be difficulties with background signals as well as drift of the control force (via drift of the force baseline, the zero of force). Both of the intermittent interaction modes, where each tip-sample interaction is brief, and in aggregate a small fraction of total imaging time, have the advantage of acting as high-pass filters, reducing low-frequency noise (e.g., 1/f, as may be generated by electronic devices). Force-distance curves induce very little problematic shear. But imaging via force curves (i.e., intermittent contact) usually must proceed more slowly than in (continuously sliding) contact mode. Also, the force per contact is measured relative to a continuously monitored zero of force, such that the latter’s drift is automatically compensated. Thus force-curve mapping requires the least “babysitting” of any mode. Dynamic mode, being an AC technique, also is little affected by background signals and at least some kinds of drift. The principal difficulties in dynamic mode derive from the nonmonotonic (with distance) complexity of probe-sample interaction, and drift in the optimal parameters for driving the resonant system. A result of the resonant dynamics is that scanning is usually performed very slowly in air, such that a single image requires ~10 minutes, or tens of minutes, to collect. One result of interaction complexity is that it can be net attractive (sometimes meaning “non-contact”) or net repulsive. One must carefully control the regime of interaction across the entire sample surface, i.e., usually avoid switching between net attractive and net repulsive regimes, to avoid artifacts. But on the good side the shear interaction can be the weakest (i.e., interaction time the shortest per encounter) and thus dynamic mode can be the least problematic. In fact non-contact imaging can allow one to image liquids (e.g., droplets, films). There are also special non-contact imaging modes that are enabled within AC methods, including electrostatic or Kelvin probe microscopy as well as magnetic force microscopy. Finally, the newest multifrequency dynamic AFM modes can provide more images and contrasting mechanisms.